Research on Scramjet External Nozzles toward Application to Future Space Transportation Systems

著者	ISONO TATSUSHI
学位授与機関	Tohoku University
学位授与番号	甲第18067号
URL	http://hdl.handle.net/10097/00125185

氏　　　　　　　名	いそ　の　たつ　し 磯　野　達　志
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）航空宇宙工学専攻
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論　文　審　査　委　員	主査　東北大学教授　浅井　圭介　東北大学教授　澤田　惠介 東北大学教授　大西　直文　東北大学客員教授　富岡　定毅 （宇宙航空研究開発機構）

論文内容要約

To replace conventional space transportation systems, that is, Expendable Launch Vehicle (ELV), research on future or advanced systems, viz., Reusable Launch Vehicle (RLV) has actively proceeded these days. Our proposed system is so-called Two-Stage-to-Orbit (TSTO), consisting of the booster and orbiter stages. Application of air-breathing engines to the RLV booster stage produces enough large weight margin required for the vehicle reusability. Devices with function required for the reusable system can be applied to the booster stage, thanks to such a weight margin. The RLV experiences extremely wide range flight condition, that is, from sea-level to high altitude and/or from static to hypersonic. Correspondingly, incoming air flow condition for the air-breathing engine also varies moment by moment. For this reason, it is necessary for conceptual design of this type of vehicle to carry out performance prediction on every component of the vehicle under huge variety of flight conditions with iterative process. Under conceptual design phase, utilizing high-fidelity CFD is unrealistic, because it requires too much computation time and cost. Therefore, performance prediction model of which calculation cost is much lighter than such CFD, is necessary to launch the conceptual design, and our present concern of Scramjet External Nozzle (SEN) is no exception. Due to efficient Airframe Propulsion Integration (API) and/or reduction in vehicle weight and friction drag, the SEN is designed as a kind of two-dimensional Single Expansion Ramp Nozzle (SERN). With the goal of further performance improvement, the bottom side wall of the nozzle, termed as the cowl, is truncated. Meanwhile, from the viewpoint of structural strength, operability, and maintainability, the propulsion system is modularized, and as a result, the SEN entrance is clustered across structural member called cell base. For the SEN with the clustered entrance, the ambient environment and the cell base highly likely affect the SEN thrust performance. The performance prediction model including the above-mentioned effects, however, has not reported even today. On the basis of such a present state of the SEN research, my graduate work had been launched, to finally establish new design concept improving the SEN thrust performance. The wind tunnel tests had been, first, carried out in order to elucidate the aforementioned two effects on the SEN flow field, and followed by an experiment-based performance prediction model had been developed and well validated by both experimental and numerical ways. Finally, we had also performed the system analysis to clarify the SEN potentials for performance improvement, utilizing our novel two-dimensional prediction model.

To begin with, for the experimental investigation, cold nitrogen gas experiments had been conducted at a supersonic free jet wind tunnel, called Pilot Wind Tunnel (PWT) located on Kakuda Space Center – Japan Aerospace Exploration Agency (JAXA-KSPC). The cold nitrogen gas issued from the test nozzle simulating the SEN flow. Test ramp having the pressure measurement ports was continuously connected to the upper side inner wall of the test nozzle, which simulated the SEN ramp wall. Dry air flow, on the other hand, was injected from facility nozzle, simulating the ambient flow. The interacting phenomenon between the SEN flow and the ambient environment was simulated by that between the test and facility nozzle flows. The experiments had been conducted under both without and with ambient flow conditions. The ambient flow effect on the SEN thrust performance was investigated by comparison of the test ramp wall pressure distributions and their normalized integrals, called pressure coefficient, between with and without ambient flow cases. Test condition was defined by test parameter, viz., Nozzle Pressure Ratio (*NPR*) which categorizes the SEN flow into so-called over-, optimum-, and under-expanded conditions. Those expanded-conditions determine first pressure waves formed in the SEN flow with the ambient flow. Shock, no, and expansion waves are shaped in the SEN flow side, for the over-, optimum-, and under-expanded conditions, respectively. Each of the counterparts forms in the ambient flow side for each corresponding expanded condition. Test results showed that the ambient flow has an effect to reduce the magnitude of the wall pressure fluctuation induced by the impinging pressure waves. The pressure waves in the ambient flow side change the physical and geometric parameters of the pressure waves in the SEN flow side. The ambient flow side waves theoretically do not appear for without ambient flow case, because of ambient static state. The slip boundary divides the flow field between the SEN and ambient flow sides. Reflections of the pressure waves by the slip boundary make the pressure waves in the SEN flow side weaker and weaker. Due to this effect, the wall pressure distributions, induced by the impinging pressure waves, are finally kept approximately constant level. Such wall pressure differences between without and with ambient flow cases are well explained by the pressure wave pattern analysis. Those new findings taught us that the wave method with covering the ambient flow effect was recommended for the performance prediction method.

Next, we addressed the investigation on the clustering effect, three differently configured test nozzles were selected as test model, of which exit simulated the SEN entrance. First one has non-clustered exit, termed as NC test nozzle, while the other two has clustered exit with larger and smaller cell bases, termed as LC and SC test nozzles, respectively. The cell base bounds each clustered flow path in the test nozzle. For LC and SC test nozzles, the wall pressure on the cell base called the cell base pressure was measured. Measured results showed that the cell base pressure can be linearly correlated with the *NPR*, for fixed SEN entrance configuration, that is, the width ratio of the cell base to the flow path. This is because, except for the smallest *NPR* case, the cell base wake closes, so that only the test nozzle exit pressure dominantly affects the cell base pressure in such a closed wake. The test results comparison demonstrated that the entrance clustering effect on the SEN ramp wall pressure distribution appears manifest on the vicinity of the SEN entrance where the inputs are made for the model, because the cell base produces the low pressure region with the cell base pressure around the SEN entrance. The presence of the cell base produces the pressure waves in spanwise direction. In the approximately-optimum-expanded condition, the heightwise pressure waves are relatively weak compared with the spanwise waves. Thus, the spanwise waves, resulting from the entrance clustering, the most remarkably affects the SEN thrust performance, in the approximately-optimum expansion case. The entrance clustering effect on the SEN thrust performance is limited except for the approximately-optimum expansion. According to those two experimental studies, we proposed first developing the prediction model counting the presence of the ambient flow, and subsequently reflecting the clustering effect coming from the presence of the cell base to the developed model by the input correction.

Here, my graduate work shifted to the next category, that is, the prediction modeling and its validation. This study proceeded utilizing the clues for modeling, obtained from the preceding experimental studies. The prediction model was developed based on the wave method, but four modifications were newly applied, to reproduce the ambient flow and the clustering effect on the SEN ramp wall pressure distribution. Each of them was named “Mach wave production,” “wave discretization,” “Riemann interaction,” and “input correction.” First modification of the Mach wave production is employed to reflect flow ununiformity at the SEN entrance to the model-calculation. The Mach waves, produced from the SEN entrance, propagate the ununiformity in the combustor flow to the SEN flow. Second modification discretizes expansion fan into series of expansion waves for computation. Each of the expansion waves is severally reflected by the slip boundary. Those are transformed into the series of compression waves, through the slip boundary reflection. The computation for Riemann interaction is applied to the prediction model as third modification. The Riemann interaction means the interactions between pressure wave and pressure wave or pressure wave and slip boundary, which have finite strength. This computation can be mathematically translated into one of the initial value problem for partial differential equation. The physical and geometric parameters of the pressure waves or slip boundary after the interactions are derived so that equalities are completed for each of the static pressures and the flow directional angles across the slip boundary. Fourth modification is the input correction to cover the entrance clustering effects. The SEN flow side inputs for the model-calculation is corrected with empirically estimated cell base pressure. Two correction methods were proposed. As for first method, the only input pressure is addressed. The input pressure is arithmetically averaged with the cell base pressure. Second one equates three conservation laws for the flow at the SEN entrance, which are mass, momentum, and energy conservations. The corrected inputs are solutions from those three conservation equations in this correction. To cover subsonic flight case, two approximating manners were proposed. These are static and low supersonic approximations. First manner approximately treats the subsonic ambient flow as static, that is, Mach 0.00. In second one, the ambient flow Mach number with subsonic state is approximated as low supersonic in the model-calculation, that is, around Mach 1.00. The validation test and high fidelity CFD-based simulation confirmed the applicability of the prediction model to the conceptual or system analysis typed studies. The prediction model well reproduced the SEN ramp wall pressure distributions for all the cases set by both the tests and simulations. The prediction error for the SEN thrust performance never exceeded 10 %, with keeping around only 7 s implementation time by personal desktop computer with quad-core 2.90 GHz processor, so that the applicability to the conceptual design was ensured by the present validation study.

Thanks to the developed prediction model and confirmation of its validity as the conceptual design tool, here, we were able to reach to the conceptual or system analysis typed study. First of all, the SEN system analysis for baseline configuration and condition was performed to grasp the SEN general behavior assuming the actual operation. As a result, recovery on the SEN ramp wall pressure is rarely attained in the assumed actual operation. The pressure recovery is obtained from the impingement of the compression type pressure waves on the SEN ramp wall. This is because, except for around take-off phase, under-expanded jet forms in the SEN flow. Thus, the SEN-ambient flows interaction generates the expansion waves from the cowl trailing edge, in most cases. This wave is called cowl expansion wave. The cowl expansion waves have a dominant role on the SEN thrust performance from Mach 1 to 5 speed range, because those impingements on the SEN ramp wall reduce the wall pressure level. From Mach 6 to 12 speed range, the ambient flow no longer affects the SEN thrust performance, because the cowl expansion waves do not enter the SEN ramp wall in high speed regime. Angles of the cowl expansion waves decrease with increase in flow Mach number at the SEN entrance, which finally prevents those waves from entering the ramp wall. The impinging cowl expansion waves produce definite drop in the SEN thrust performance, from low to middle speed regimes. Accordingly, we proposed novel design concept for the SEN, based on its two-dimensional flow characteristics. One of the propositions for the new design methodology were confirmed by the additional system analysis. This is SEN entrance height extension to reduce the number of the cowl expansion waves impinging on the SEN ramp wall. Around 28 % height extension from the baseline configuration connects to around 15 % SEN thrust performance improvement under the middle speed regime. More practical system analysis was additionally performed, that is, the system analysis for the combustor followed by the SEN under set constraint. In addition to our developed performance prediction model for the SEN, we utilized previously reported combustor model. The constraint was set so that design change in the combustor with SEN did not affect performances of the other elements, such as, intake or airframe. The design modification is to vary ratio between the combustor and SEN portions in the propulsion system. The analyzing results demonstrated that the SEN has more potential to improve the whole thrust performance of the propulsion system than the combustor, so that sparing larger portion for the SEN leads whole thrust performance improvement.

As last part of my graduate work, we addressed relocation of the rocket engine from inside the combustor to on the SEN ramp wall to form so-called Rocket Spike Nozzle (RSN). This design modification is to maintain the ramp wall pressure high level by the rocket exhaust, and also mitigate the severe thermal load in the combustor. The rocket engine inside the combustor produces severe thermal load, because the rocket exhaust with high temperature is surrounded by the walls in this configuration. We can call this nozzle system the SEN-RSN hybrid nozzle, because of its configuration. Three rocket locations, viz., the RSN locations on the SEN ramp wall were set. Computation showed that the nozzle thrust performance is determined through interrelationship between the pressure wave pattern in the SEN flow and the RSN location. Since the hybrid nozzle produces much larger thrust than single SEN under appropriate operation and location, we finally concluded that this nozzle system has great potential to improve overall propulsion system performance.